Discovery of a Brown Dwarf Companion to Gliese 570ABC: A 2MASS T Dwarf Significantly Cooler than Gliese 229B

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ABSTRACT

We present the discovery of a widely separated (258″.3±0″.4) T dwarf companion to the Gl 570ABC system. This new component, Gl 570D, was initially identified from the Two Micron All Sky Survey (2MASS). Its near-infrared spectrum shows the 1.6 and 2.2 μm CH_4 absorption bands characteristic of T dwarfs, while its common proper motion with the Gl 570ABC system confirms companionship. Gl 570D (M_J = 16.47±0.07) is nearly a full magnitude dimmer than the only other known T dwarf companion, Gl 229B, and estimates of L = (2.8±0.3)x10^{-6} $L_\odot$ and T_{eff} = 790±40 K make it significantly cooler and less luminous than any other known brown dwarf. Using evolutionary models by Burrows et al. and an adopted age of 2-10 Gyr, we derive a mass estimate of 50±20 M_{Jup} for this object.

Subject headings: infrared: stars — stars: binaries: visual — stars: fundamental parameters — stars: individual (Gl 570D) — stars: low mass, brown dwarfs

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1. Introduction

The investigation of brown dwarfs was revolutionized by the discovery of a low-mass companion around the nearby M dwarf Gl 229. Gl 229B (Nakajima et al. 1995) proved to be the coolest and intrinsically faintest object observed outside the solar system, with an effective temperarture (T_{eff}) of 960±70 K (Marley et al. 1996) and luminonsity (L) of $(6.6\pm0.6)\text{x}10^{-6}$ $L_{\odot}$ (Leggett, Geballe, & Brown 1999). Strong methane absorption features at 1.6 and 2.2 μm confirm this object as a genuine brown dwarf, and its distance of 5.77 pc (Perryman et al. 1997) and age of $\approx$ 1 Gyr (Nakajima et al. 1995) allow ready comparison with evolutionary and spectral models. As such, Gl 229B has been a benchmark in the study of brown dwarfs.

Direct detection techniques, like those that discovered Gl 229B, have been used for the last 15 years to search for brown dwarfs around nearby stars. Such searches have been conducted by various groups via imaging (Probst 1983; Jameson, Sherrington, & Giles 1983; Shipman 1986; Zuckerman & Becklin 1987; Skrutskie, Forrest, & Shure 1989; Henry & McCarthy 1990; Kumar 1990; Henry 1991; Zuckerman & Becklin 1992; Simons, Henry, & Kirkpatrick 1996; Rebolo et al. 1998; Oppenheimer 1999) and spectroscopy (Kirkpatrick & McCarthy 1994) of nearby main sequence stars and white dwarfs. Despite the large samples involved, only two *bona fide* brown dwarf companions have been directly detected, the aforementioned Gl 229B and the young brown dwarf G 196-3B (Rebolo et al. 1998). Kirkpatrick et al. (2000) have recently identified two additional L-type brown dwarf companions.

Since most of these searches have been confined to a narrow field of view around the primary (typically 10-60″), widely separated companions[10] may be missed. Indeed, both G 196-3B and Gl 229B are less than 20″ from their primary. Field surveys, such as the Two Micron All Sky Survey (Skrutskie et al. 1997, hereafter 2MASS), the DEep Near Infrared Survey (Epchtein et al. 1997, hereafter DENIS), and the Sloan Digital Sky Survey (York et al. 1999, hereafter SDSS), overcome this limitation.

We are currently searching the 2MASS catalogs for field T dwarfs (Burgasser et al. 1998), brown dwarfs spectrally identified by CH_4 absorption bands at 1.6 and 2.2 μm (Kirkpatrick et al. 1999). One of our latest discoveries, 2MASSW J1457150-212148 (hereafter Gl 570D), has been confirmed as a widely separated, common proper motion companion to the Gl 570ABC system. This system is comprised of a K4V primary and a M1.5V-M3V close binary (Duquennoy & Mayor 1988; Mariotti et al. 1990; Forveille et al. 1999) at a distance of 5.91±0.06 pc (Perryman et al. 1997). In §2 we describe the selection of this object from the 2MASS database, review subsequent observations, and establish its common proper motion with Gl 570ABC. In §3 we estimate L and T_{eff} of Gl 570D based on its distance and brightness, and make T_{eff} and mass estimates using the evolutionary models of Burrows et al. (1997). In §4 we summarize our results.

[10]We adopt an observational definition for "widely separated" as angular separation greater than 100″; see Fischer & Marcy (1992).

2. Selection and Identification

2.1. Selection and Confirmation of Gl 570D

Gl 570D was initially selected as a T dwarf candidate from the 2MASS Point Source Catalog. T dwarf candidates were required to have J- and H-band detections with $J < 16$ (2MASS signal-to-noise ratio ~ 10 limit), $J\text{-}H < 0.3$ and $H\text{-}K_s < 0.3$ (limit or detection), $|b| > 15^o$ (to eliminate source confusion in the Galactic plane), and no optical counterpart in the USNO-A catalog (Monet et al. 1998) within $10''$. Close optical doubles not identified by USNO-A and proper motion stars were eliminated by examination of Digitized Sky Survey (DSS) images of the SERC-J and AAO SES (Morgan et al. 1992) surveys. Our search criteria are also sensitive to minor planets, due to their intrinsically blue near-infrared colors (Veeder et al. 1995; Sykes et al. 1999), lack of optical counterpart, and point-like appearance due to the short 2MASS exposure time (7.8 seconds). Follow-up near-infrared imaging to eliminate these objects from our candidate pool was carried out on the Cerro Tololo InfraRed IMager (CIRIM[11]) at the Cerro Tololo Interamerican Observatory (CTIO) 1.5m during 1999 July 23-25 (UT). Gl 570D was one of only 11 candidates detected in these observations (the remaining candidates were likely asteroids). Optical images of the Gl 570D field from the SERC-J and AAO SES surveys, as well as 2MASS J- and K_s-band images, are shown in Figure 1; the Gl 570ABC triple can be seen in the lower left corner. No optical counterpart is seen either at the current or projected (proper motion) position of Gl 570D, indicating very red optical-infrared colors. Table 1 lists 2MASS J, H, and K_s magnitudes (rows [1]-[3]) and colors (rows [4]-[6]) for Gl 570D, as well as measurements for G 196-3B and Gl 229B taken from the literature (Matthews et al. 1996; Rebolo et al. 1998) and from 2MASS data. Note that Gl 570D has blue near-infrared colors, similar to Gl 229B.

2.2. Spectral Data

The 1.6 and 2.2 μm fundamental overtone CH_4 bands were identified in Gl 570D from near-infrared spectral data taken with the Ohio State InfraRed Imager/Spectrometer (Depoy et al. 1993, hereafter OSIRIS) on the CTIO 4m on 1999 July 27 (UT). Using OSIRIS's cross-dispersion mode, we obtained continuous 1.2-2.3 μm spectra with $\Delta\lambda/\lambda \approx 1200$. The slit width was fixed at $1''.2$ for all observations. The object was placed on the slit via direct image centroiding, and then stepped across the slit in seven positions at $3''$ intervals (to offset fringing and detector artifacts) with 120-second integrations at each position. A total of 3360 seconds of integration time was acquired. Spectra were then extracted using standard IRAF[12] reduction packages. Raw data were flat-fielded using observations of the 4m illuminated dome spot and software generously supplied

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[11]See http://www.ctio.noao.edu/instruments/ir_instruments/cirim/cirim.html for more information on CIRIM.

[12]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

by R. Blum at CTIO. Object spectra were extracted using a template from a bright standard star. Wavelength calibration was computed from OH sky lines. Finally, telluric corrections and relative flux calibration was done using observations of the nearby A1V star HR 5696 (Hoffliet & Jaschek 1982).

The near-infrared spectrum of Gl 570D is shown in Figure 2, along with data for the SDSS T dwarf SDSSp J162414.37+002915.6 (Strauss et al. 1999, hereafter SDSS1624+00) obtained on the same night. Both spectra are normalized at 1.55 μm. Gl 229B spectral data from Geballe et al. (1996), also normalized at 1.55 μm, are overlain on both for comparison (dark line). The 1.6 and 2.2 μm bands are present in all three brown dwarfs. There is a striking similarity in the spectral morphology of these objects; however, the overlaid spectrum of Gl 229B highlights subtle differences. There appears to be a slight enhancement in flux (relative to Gl 229B) in SDSS1624+00 at the blue edge of the 1.3 μm absorption feature and at the base of the 1.6 μm CH_4 absorption band. Conversely, the spectrum of Gl 570D does not show these features and in fact appears deficient at the 1.5 μm H_2O-CH_4 wing and the 2.1 μm flux peak. Although these variations are subtle (particularly given the low signal-to-noise in the OSIRIS data), they can be explained if we assume that SDSS1624+00 is warmer than Gl 229B and Gl 570D cooler. In this scenario, we would expect the CH_4 bands at 1.4 and 1.6 μm to deepen as the observed temperature decreases. Increased suppression of flux at 2.1 μm could also be due to increased H_2 absorption at lower temperatures (Burgasser et al. 1999). This hypothesis is supported by detections of FeH and CrH in SDSS1624+00 (Burgasser et al. 2000), which suggests that it is a warm T dwarf, while the coolness of Gl 570D is supported by evidence discussed below. Naturally, other effects such as metallicity or gravity could also be important, and a more thorough study of T dwarf near-infrared spectral signatures is currently in progress.

2.3. Association with Gl 570ABC

The proximity of the bright Gl 570ABC triple led us to suspect possible association for this object. Fortunately, the system has a relatively high proper motion of $2\farcs012 \pm 0\farcs002$ yr^{-1} (Perryman et al. 1997), permitting a quick check for common motion. In addition, multiple sampling and the 2MASS position reconstruction strategy results in a higher astrometric accuracy ($\sim 0\farcs3$[13]) than the raw pixel scale of the 2MASS detectors ($2''$), sufficient to measure the motion of this system on a one year timescale. The original 2MASS scan of the Gl 570D field was taken on 1998 May 16 (UT); a second scan was obtained on 1999 July 29 (UT). Table 2 summarizes the resulting astrometric data, indicating that all components have a common sky motion of $2\farcs3 \pm 0\farcs4$ at position angle $155 \pm 4°$. The mean motion of all other objects in the field is $0\farcs0 \pm 0\farcs2$ in RA and $0\farcs2 \pm 0\farcs1$ in declination. This statistically significant common proper motion confirms companionship. Gl 570D

[13]Cutri, R. M., et al. Explanatory Supplement to the 2MASS Spring 1999 Incremental Data Release: http://www.ipac.caltech.edu/2mass/releases/spr99/doc/explsup.html.

lies $258''.3\pm0''.4$ from the K4V primary, a projected physical separation of 1525±15 AU. Note that this is an order of magnitude larger than the A-BC separation ($24''.7\pm0''.4$) and over four orders of magnitude larger than the B-C separation of $0''.1507\pm0''.0007$ (Forveille et al. 1999). The separation of Gl 570D is compared to those of G 196-3B and Gl 229B in Table 1 (rows [7]-[8]).

3. Estimates of the Physical Properties of Gl 570D

Distance moduli and absolute J magnitudes for the three brown dwarf companions G 196-3B, Gl 229B, and Gl 570D, based on the distances to their respective primaries, are listed in Table 1 (rows [9]-[10]). Gl 570D is nearly a magnitude fainter than Gl 229B at all three near-infrared bands. If we assume a Gl 229B J-band bolometric correction of 2.19±0.10 (Leggett, Geballe, & Brown 1999) and a radius of $(7.0\pm0.5)\times10^9$ cm $\approx$ 1 Jupiter radius, we then derive L = $(2.8\pm0.3)\times10^{-6}$ $L_\odot$ and T_{eff} = 750±50 K, roughly 200 K cooler than Gl 229B, making Gl 570D the least luminous and coolest brown dwarf thus far detected. More accurate determinations of the effective temperature and mass of Gl 570D can be made using brown dwarf evolutionary models, but only if we can constrain its age. The proximity of Gl 570ABC has permitted detailed studies of kinematic properties, activity, and high energy emission (UV and X-ray), leading to various age estimates for the system (Leggett 1992; Poveda et al. 1993; Fleming, Schmitt, & Giampapa 1995). There is a general consensus that this system is older than 2 Gyr, supported by the lack of activity in the close BC binary (Reid, Hawley, & Gizis 1995). The solar-like metallicity of Gl 570ABC (Forveille et al. 1999) and the system space motion of $\approx$ 60 km s^{-1} (Leggett 1992) constrains formation to the Galactic disk, which establishes a rough upper limit of about 10 Gyr. Using the evolutionary models of Burrows et al. (1997) and adopting log $(L/L_\odot)$ = -5.56±0.05 and t = 6±4 Gyr, we derive values of T_{eff} = 790±40 K, and M = 50±20 M_{Jup}[14] (Table 1, rows [13]-[14]). The effective temperature is consistent with the brightness estimate above, and is significantly lower than those of G 196-3B and Gl 229B. Perhaps most interesting is that Gl 570D could possibly be the most massive of these three brown dwarfs. This accentuates the difficulty of basing comparisons of brown dwarfs on brightness and/or temperature alone, and the importance of age determinations in deriving the physical properties of cool brown dwarfs. More accurate estimates of this object's properties require spectral modeling and additional broad-band photometry, and will be addressed in a future paper.

4. Summary

We have presented near-infrared photometric and spectral data on a T dwarf companion to the Gl 570ABC system. The presence of CH_4 verifies the brown dwarf status of this object, while proper motion measurements made by 2MASS confirm its association. Parallax measurements and

[14] 1 M_{Jup} = 1.9×10^{33} grams = 0.0095 $M_\odot$.

age estimates for this system, along with evolutionary models from Burrows et al. (1997), allow us to derive L = $(2.8\pm0.3)\times10^{-6}$ $L_\odot$, T_{eff} = 790±40 K, and M = 50±20 M_{Jup}. Thus, this object is cooler and less luminous than the only other known T dwarf companion, Gl 229B, and serves as a new standard in understanding the properties of cool brown dwarfs. Near-infrared spectral data show possible temperature-dependent feature variations, although further study is warranted. The wide separation of this companion ($258''.3\pm0''.4$) suggests that a large number of substellar companions may be pretermitted, as they lie beyond the detection field of previous searches. Field surveys, then, could contribute greatly to the detection of substellar companions.

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Fig. 1.— 2MASS J- and K_s-band images of Gl 570D, along with two optical images from SERC-J and AAO-SES at two different epochs. Each field is 5′ x 5′ with north up and east to the left. The Gl 570ABC triple is seen in the lower left corner (the BC binary is unresolved). Gl 570D is indicated in the 2MASS images by a 20″ x 20″ box, while its projected location due to motion is indicated in each optical image. No optical counterpart is seen in either of these images, limiting R-J $\gtrsim$ 6. The blue J-K_s color of Gl 570D (J-K_s = 0.06±0.23) is evident as the object is barely detectable at K_s.

Fig. 2.— Near-infrared spectral data for Gl 570D (bottom) and SDSS1624+00 (top). Both are normalized at 1.55 μm. Spectral data for Gl 229B from Geballe et al. (1996) are overlaid for comparison (dark line). The data are strikingly similar, as CH_4 absorption features at 1.3, 1.6, and 2.2 μm are clearly seen in all three objects, as are broadened H_2O absorption bands at 1.2, 1.4, and 1.9 μm. Absorption due to H_2 longward of $\sim$ 1.9 μm is probably also present. Despite the strong similarities, there are some variations in flux near the 1.3 and 1.5 μm H_2O-CH_4 absorption wings, the 1.6 μm CH_4 absorption band, and the 2.1 μm flux peak, all of which are probably attributable to temperature differences between these objects.

Table 1. Properties of Confirmed Companion Brown Dwarfs.

	Property	G 196-3B[a]	Gl 229B[b]	Gl 570D[c]
(1)	J	14.55±0.05	14.33±0.05	15.33±0.05
(2)	H	—	14.35±0.05	15.28±0.09
(3)	K_s	12.45±0.10	14.42±0.05	15.27±0.17
(4)	J-H	—	−0.02±0.07	0.05±0.11
(5)	H-K_s	—	−0.07±0.07	0.01±0.11
(6)	J-K_s	2.10±0.11	−0.09±0.07	0.06±0.23
(7)	ρ, PA ($''$, ^{o})	16.2, 210	7.8±0.1, 163	258.3±0.4, 316 (A-D) 234.1±0.4, 317 (BC-D)
(8)	ρ (AU)	340±100	44.9±0.6	1525±15 (A-D) 1385±15 (BC-D)
(9)	Distance Modulus[d]	1.6±0.6	−1.19±0.07	−1.14±0.05
(10)	M_J	12.6±1.4	15.52±0.06	16.47±0.07
(11)	log (L/L⊙)	$-3.8^{+0.2}_{-0.3}$	−5.18±0.04	−5.56±0.05[e]
(12)	Age (Gyr)	0.02-0.3	0.5-1.0	2-10
(13)	T_{eff} (K)	1800±200	960±70	790±40[f]
(14)	M (M_{Jup})	25^{+15}_{-10}	43±12	50±20[f]

[a]Data from Rebolo et al. (1998). Magnitudes are corrected to J_{CIT} and K_{CIT} from the UKIRT system using color transformations from Leggett, Allard, & Hauschildt (1998).

[b]Data from Nakajima et al. (1995); Marley et al. (1996); Leggett, Geballe, & Brown (1999).

[c]Data from epoch 1998 May 16 (UT).

[d]Data for Gl 229A and Gl 570A from Hipparcos (Perryman et al. 1997).

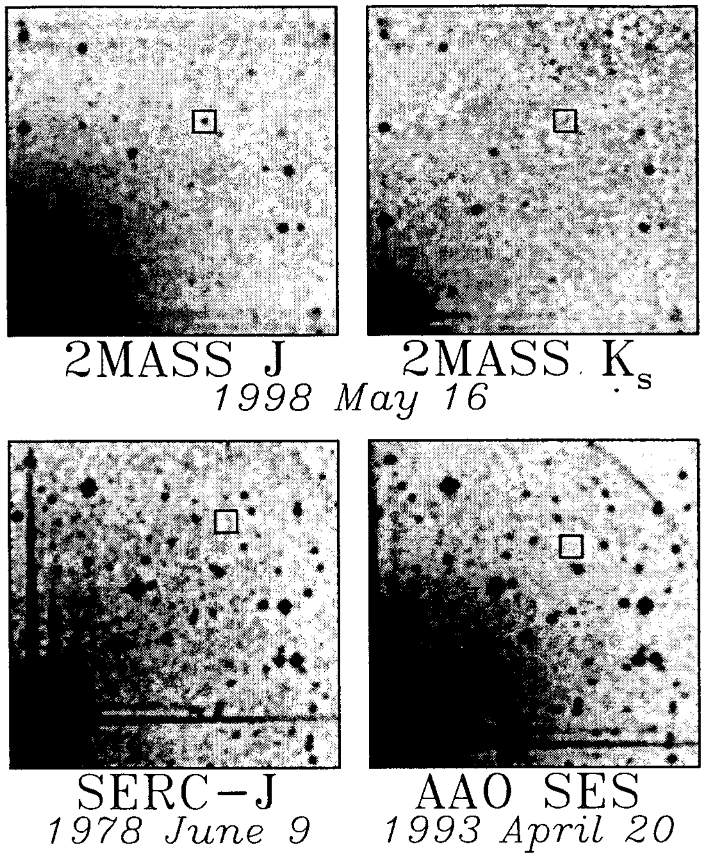
[e]Assuming J-band bolometric correction of 2.19±0.10 from Leggett, Geballe, & Brown (1999).

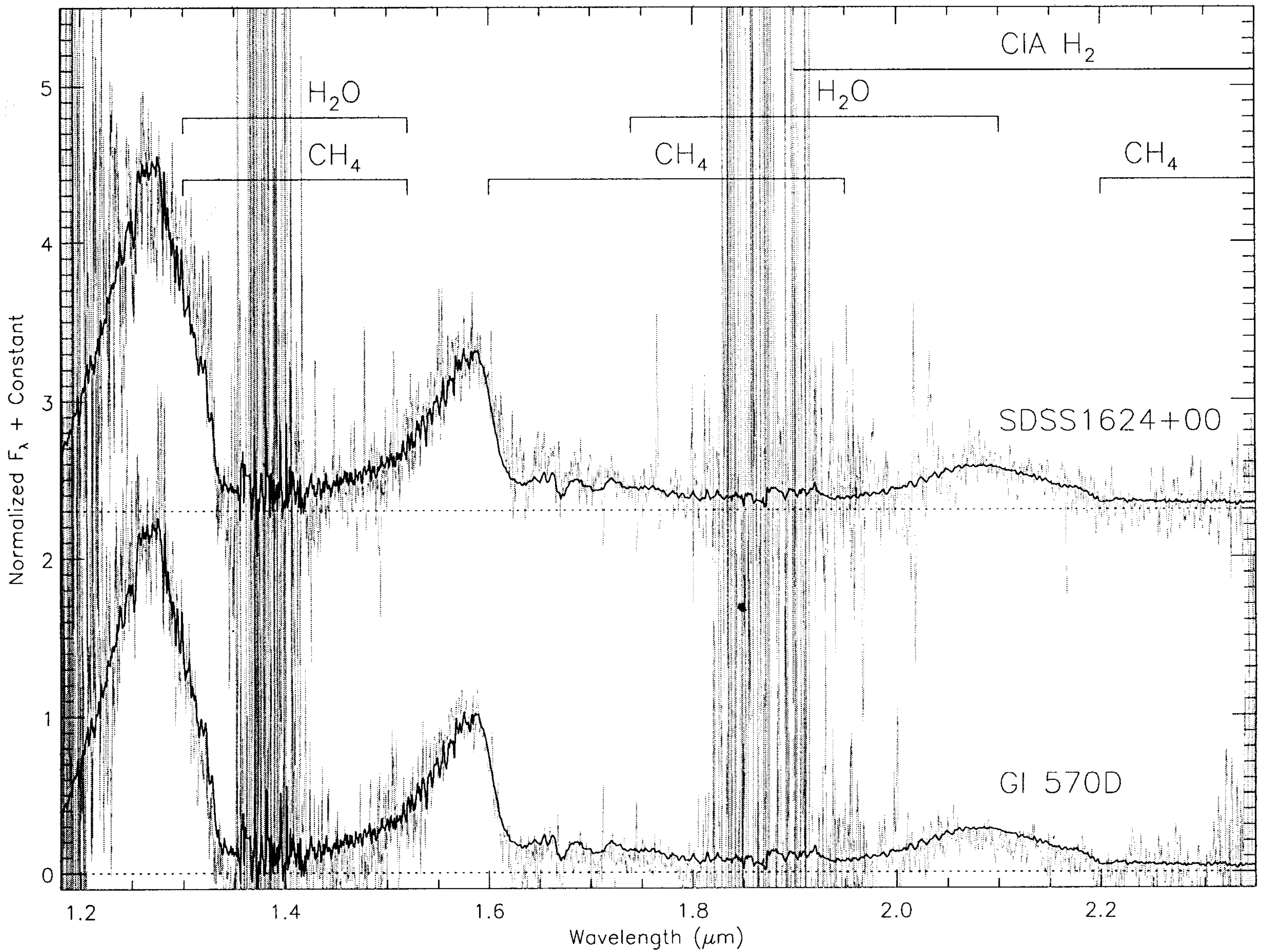
[f]Derived from evolutionary models by Burrows et al. (1997).

Table 2. 2MASS Astrometry for Gl 570ABCD.

Component	1998 May 16 (UT) RA[a]	Decl.	1999 July 29 (UT) RA	Decl.	Difference $''$	$^\circ$
A	14:57:27.87	-21:24:52.72	14:57:27.93	-21:24:54.87	2.3±0.4	156
BC	14:57:26.42	-21:24:38.54	14:57:26.49	-21:24:40.77	2.4±0.4	159
D	14:57:14.96	-21:21:47.79	14:57:15.04	-21:21:49.82	2.3±0.4	151

[a] All coordinates are epoch J2000.0.


2MASS J
2MASS K_s
1998 May 16
SERC–J
1978 June 9
AAO SES
1993 April 20


CIA H2
H2O
CH4
H2O
CH4
CH4
SDSS1624+00
Gl 570D
Normalized Fλ + Constant
Wavelength (μm)
0
1
2
3
4
5
1.2
1.4
1.6
1.8
2.0
2.2